Electroweak probes in the search of the strangeness content in the nucleon

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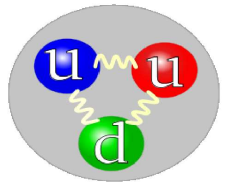
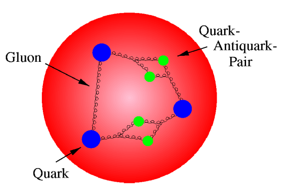
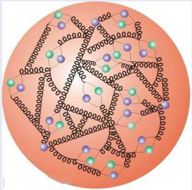
Internal structure of the nucleon

Constituent quarks



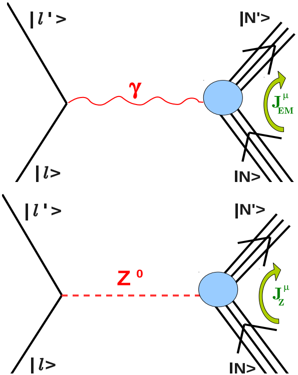
Sea quark $\bar{q}q \to \bar{s}s$-pair contribution





Probes to study the nucleon structure

- **Electrons.**
  Mainly, **EM interaction**.
  EM structure of the nucleon.
- **Neutrinos.**
  Weak interaction (we focus on Neutral Current processes).
  Weak structure of the nucleon.



General expression of the current operator of the (free) nucleon

From general symmetry properties:

$$\hat{J}^{\mu\,(p,n)}_{\rm EM} = \gamma^\mu \frac{G_E^{(p,n)} + \tau G_M^{(p,n)}}{1+\tau} + i\frac{\sigma^{\mu\nu}Q_\nu}{2M}\frac{G_M^{(p,n)} - G_E^{(p,n)}}{1+\tau}$$

$$\hat{J}^{\mu\,(p,n)}_{Z} = \gamma^\mu \frac{\widetilde{G}_E^{(p,n)} + \tau \widetilde{G}_M^{(p,n)}}{1+\tau} + i\frac{\sigma^{\mu\nu}Q_\nu}{2M}\frac{\widetilde{G}_M^{(p,n)} - \widetilde{G}_E^{(p,n)}}{1+\tau} + \gamma^\mu\gamma^5 G_A^{(p,n)}$$

The EM structure of the nucleon is parametrized by the EM form factors: $G_{E,M}^{(p,n)}$.
The WNC structure of the nucleon is parametrized by the WNC form factors: $\widetilde{G}_{E,M}^{(p,n)}$, in the vector sector; and $G_A^{(p,n)}$ in the axial-vector sector.

Flavor decomposition of the form factos: We consider the contributions of the flavors: u, d and s.

$$\begin{aligned}
G_{E,M}^{p(n)} &= \frac{2}{3} G_{E,M}^{\mathbf{u(d)}} - \frac{1}{3}\left(G_{E,M}^{\mathbf{d(u)}} + G_{E,M}^{\mathbf{s}} \right) , \\
\widetilde{G}_{E,M}^{p(n)} &= (1 - \frac{8}{3}\sin^2\theta_W) G_{E,M}^{\mathbf{u(d)}} - (1 - \frac{4}{3}\sin^2\theta_W) \left(G_{E,M}^{\mathbf{d(u)}} + G_{E,M}^{\mathbf{s}} \right) , \\
G_A^{p(n)} &= -G_A^{\mathbf{u(d)}} + G_A^{\mathbf{d(u)}} + G_A^{\mathbf{s}} ,
\end{aligned}$$

Flavor decomposition of the form factos: We only considered the contributions of the flavors: u, d and s.

$$\boxed{G^{p(n)}_{E,M}} = \frac{2}{3} G^{\mathbf{u(d)}}_{E,M} - \frac{1}{3}\left(G^{\mathbf{d(u)}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) , \quad \boxed{G^{p(n)}_{E,M}} \text{well known}$$

$$\widetilde{G}^{p(n)}_{E,M} = (1 - \frac{8}{3}\sin^2\theta_W) G^{\mathbf{u(d)}}_{E,M} - (1 - \frac{4}{3}\sin^2\theta_W)\left(G^{\mathbf{d(u)}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) ,$$

$$G^{p(n)}_{A} = \boxed{-G^{\mathbf{u(d)}}_{A} + G^{\mathbf{d(u)}}_{A}} + G^{\mathbf{s}}_{A} , \quad \boxed{2G^{(3)}_{A} = G^{\mathbf{u}}_{A} - G^{\mathbf{d}}_{A}} \text{ “known”}$$

Flavor decomposition of the form factos: We only considered the contributions of the flavors: u, d and s.

$$\boxed{G_{E,M}^{p(n)}} = \frac{2}{3} G_{E,M}^{\mathbf{u(d)}} - \frac{1}{3}\left(G_{E,M}^{\mathbf{d(u)}} + G_{E,M}^{\mathbf{s}}\right), \quad \boxed{G_{E,M}^{p(n)}} \text{ well known}$$

$$\widetilde{G}_{E,M}^{p(n)} = (1 - \frac{8}{3}\sin^2\theta_W) G_{E,M}^{\mathbf{u(d)}} - (1 - \frac{4}{3}\sin^2\theta_W)\left(G_{E,M}^{\mathbf{d(u)}} + G_{E,M}^{\mathbf{s}}\right),$$

$$G_A^{p(n)} = \boxed{-G_A^{\mathbf{u(d)}} + G_A^{\mathbf{d(u)}}} + G_A^{\mathbf{s}}, \quad \boxed{2G_A^{(3)} = G_A^{\mathbf{u}} - G_A^{\mathbf{d}}} \text{ “known”}$$

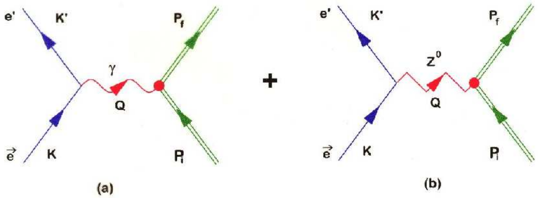
If one could measure $G_{E,M}^{(s)}$ and $G_A^{(s)}$, the equations could be trivially solved.
That is: the determination of the strangeness content in the nucleon could help to disentangle the role played by each flavor in the electroweak structure of the nucleon.

How to study the strange form factors?

We have analysed two different processes

1^{er}) Parity Violation Asymmetry ($\mathcal{A}^{PV}$)

$$\boxed{\vec{e} + p \longrightarrow e + p} \longmapsto \mathcal{A}^{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

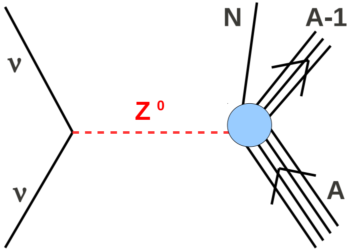


How to study the strange form factors?

We have analysed two different processes

2^{nd}) Neutral Current Quasielastic Neutrino Nucleus Scattering: MiniBooNE experiment - (target: CH_2).

$$\boxed{\nu + A \longrightarrow \nu + N + (A-1)}$$



Parity violation asymmetry

Sources of theoretical errors and their impact on $\mathcal{A}^{PV}$

EM form factor	$< 5\%$
Radiative corrections (higher order processes)	$\sim 5\%$ (at worst) $(\lvert Q^2 \rvert < 1)$
Axial form factor (axial mass, M_A)	$\sim 5\%$
Electric and magnetic strangeness (ρ_s and μ_s)	higher than 50%

Reference: Physics Report 524 (2013) 1-35;
R. González-Jimenez, J. A. Caballero and T. W. Donnelly

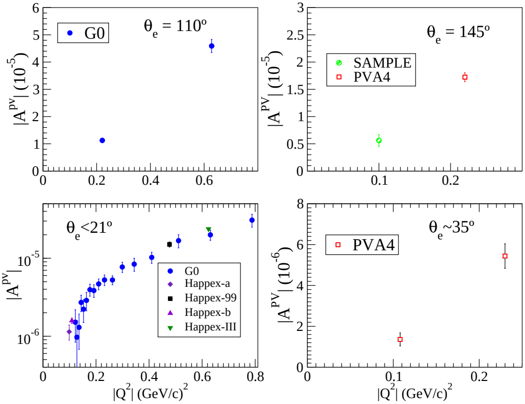


Figure: PV asymmetry data. Each panel corresponds to a different scattering angle.

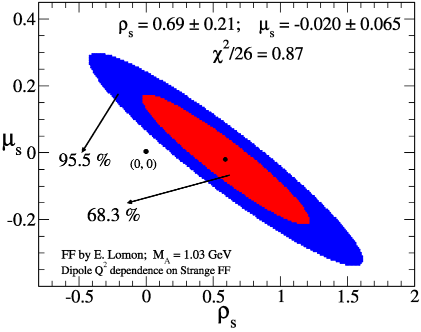


Figure: World data constraint in the $\mu_s - \rho_s$ plane. 1-σ (red) and 2-σ (blue) allowed region.

- Electric strangeness, $G_E^{(s)} \longleftrightarrow \rho_s$, and Magnetic strangeness, $G_M^{(s)} \longleftrightarrow \mu_s$.
- χ^2 analysis using all the experimental data up to date.
- Confidence contours around the point of maximum likelihood (68.3% and 95.5%) for the strange parameters: electric, ρ_s, and magnetic, μ_s.
- The (0,0) point (nule strangeness) is out of the 2σ contour.

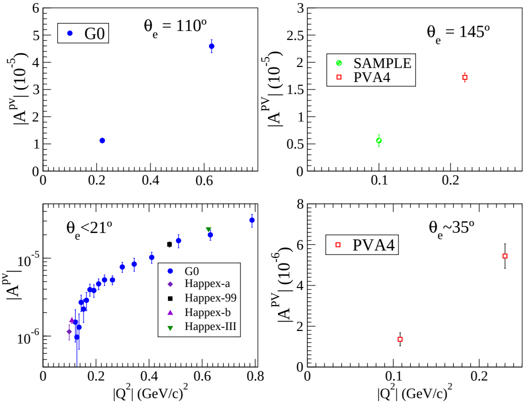


Figure: PV asymmetry data with our prediction for some representative values of ρ_s and μ_s. The colored band represents the effect of the axial mass.

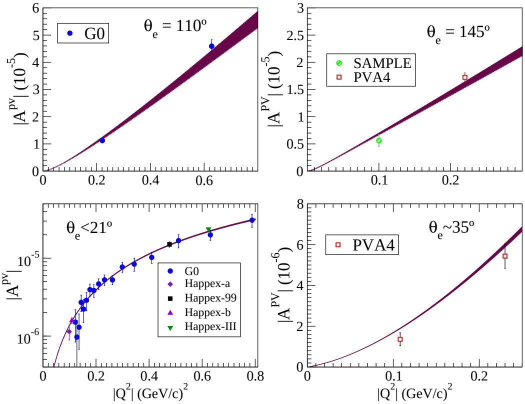


Figure: PV asymmetry data with our prediction for some representative values of ρ_s and μ_s. The colored band represents the effect of the axial mass.

MiniBooNE (NCQE neutrino-CH_2) observables

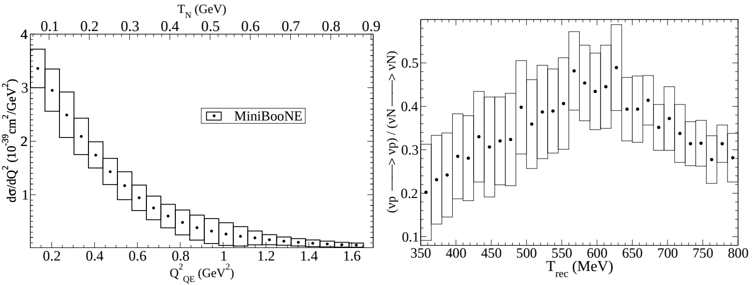


Figure: MiniBooNE data. Cross section (left) ratio (right).

Reference: Physics Letters B 718 (2013) 1471-1474;
R. González-Jimenez, M. V. Ivanov, M. B. Barbaro, J. A. Caballero and J. M. Udias

Sources of theoretical errors and their impact on the observables

	Cross section	Ratio $(\frac{\sigma_p}{\sigma_p+\sigma_n})$
EM form factor	$< 1\%$	$< 1\%$
Electric strangeness ($\rho_s \pm 1\sigma$)	$<< 1\%$	$< 1\%$
Magnetic strangeness ($\mu_s \pm 1\sigma$)	$<< 1\%$	$< 5\%$
Nuclear model (FSI)	10-30% (low to high $\lvert Q^2 \rvert$)	$< 5\%$
Axial form factor $M_A \in (1.03,\ 1.45)$	$20 - 50\%$ (low to high $\lvert Q^2 \rvert$)	$\sim 7 - 8\%$
Axial strangeness $g_A^{(s)} \in (-0.3,\ 0.3)$	$< 1\%$	$\sim 18\%$

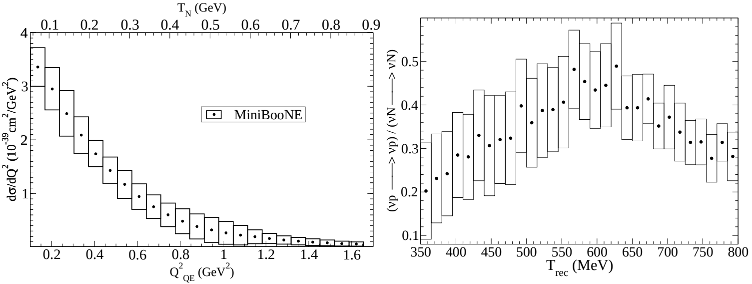


Figure: MiniBooNE data. Cross section (left). Ratio (right).

(1°): We fit M_A using the cross section data. $M_A = 1.34 \pm 0.06$ GeV (RMF model) and $M_A = 1.42 \pm 0.06$ (SuSA).

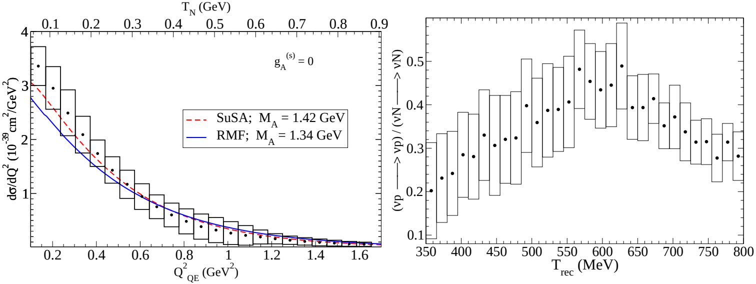


Figure: MiniBooNE data. Cross section (left). Ratio (right).

(1^o): We fit M_A using the cross section data. $M_A = 1.34 \pm 0.06$ GeV (RMF model) and $M_A = 1.42 \pm 0.06$ (SuSA).
(2^o): We fit $g_A^{(s)}$ using the ratio data (and the previous M_A value). $g_A^{(s)} = 0.04 \pm 0.28$ (RMF model) and $g_A^{(s)} = -0.06 \pm 0.31$.

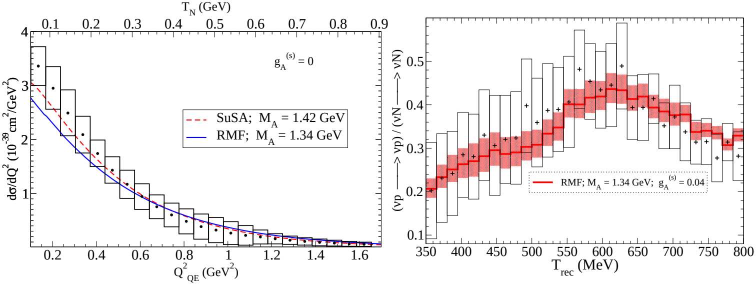


Figure: MiniBooNE data. Cross section (left). Ratio (right).

(1^o): We fit M_A using the cross section data. $M_A = 1.34 \pm 0.06$ GeV (RMF model) and $M_A = 1.42 \pm 0.06$ (SuSA).
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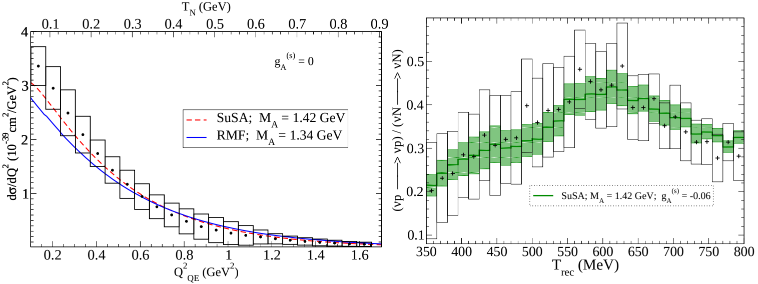

Figure: MiniBooNE data. Cross section (left). Ratio (right).

Summary and Conclusions

- The electroweak structure of the nucleon have been investigated through the study of the nucleon form factors.
- All PV asymmetry data up to date have been used to constrain the electric and magnetic strangeness content of the nucleon.
- The NCQE neutrino cross section MiniBooNE data have been used to fit the axial mass.
- The proton/neutron ratio data from the neutrino NCQE MiniBooNE experiment have been employed to constrain the axial strangeness content of the nucleon.
- Further investigations are needed before definitive conclusions are drawn.

Thank you for your attention

Flavor descomposition

Since the nucleons are made of quarks, the nucleon current is the nucleon matrix element of the quark current operators:

$$
\begin{aligned}
J_\mu^{EM} &= \langle N_f | \hat{J}_\mu^{EM} | N_i \rangle = \langle N_f | \sum_{q=u,d,s} Q_q \bar{u}_q \gamma_\mu u_q | N_i \rangle \\
J_\mu^{Z,V} &= \langle N_f | \hat{J}_\mu^{Z,V} | N_i \rangle = \langle N_f | \sum_{q=u,d,s} g_V^q \bar{u}_q \gamma_\mu u_q | N_i \rangle \\
J_\mu^{Z,A} &= \langle N_f | \hat{J}_\mu^{Z,A} | N_i \rangle = \langle N_f | \sum_{q=u,d,s} g_A^q \bar{u}_q \gamma_\mu \gamma_5 u_q | N_i \rangle \, ,
\end{aligned}
$$

We only consider the contributions of the pairs: $\bar{u}u$, $\bar{d}d$ and $\bar{s}s$. The contribution of the heavier quarks is expected to be of the order of 10^{-4} (10^{-2}) for the vector (axial-vector) currents.

Flavor decomposition of the vector form factos:

$$G^{p}_{E,M} = \frac{2}{3} G^{\mathbf{u}}_{E,M} - \frac{1}{3}\left(G^{\mathbf{d}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) ,$$

$$G^{n}_{E,M} = \frac{2}{3} G^{\mathbf{d}}_{E,M} - \frac{1}{3}\left(G^{\mathbf{u}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) ,$$

$$\widetilde{G}^{p}_{E,M} = (1 - \frac{8}{3}\sin^2\theta_W) G^{\mathbf{u}}_{E,M} - (1 - \frac{4}{3}\sin^2\theta_W)\left(G^{\mathbf{d}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) ,$$

$$\widetilde{G}^{n}_{E,M} = (1 - \frac{8}{3}\sin^2\theta_W) G^{\mathbf{d}}_{E,M} - (1 - \frac{4}{3}\sin^2\theta_W)\left(G^{\mathbf{u}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) ,$$

Flavor decomposition of the vector form factos:

$$\boxed{G^p_{E,M}} = \frac{2}{3} G^{\mathbf{u}}_{E,M} - \frac{1}{3}\left(G^{\mathbf{d}}_{E,M} + G^{\mathbf{s}}_{E,M}\right), \quad \boxed{G^p_{E,M}} \text{ well known}$$

$$\boxed{G^n_{E,M}} = \frac{2}{3} G^{\mathbf{d}}_{E,M} - \frac{1}{3}\left(G^{\mathbf{u}}_{E,M} + G^{\mathbf{s}}_{E,M}\right), \quad \boxed{G^n_{E,M}} \text{ relatively well known}$$

$$\widetilde{G}^p_{E,M} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G^{\mathbf{u}}_{E,M} - \left(1 - \frac{4}{3}\sin^2\theta_W\right)\left(G^{\mathbf{d}}_{E,M} + G^{\mathbf{s}}_{E,M}\right),$$

$$\widetilde{G}^n_{E,M} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G^{\mathbf{d}}_{E,M} - \left(1 - \frac{4}{3}\sin^2\theta_W\right)\left(G^{\mathbf{u}}_{E,M} + G^{\mathbf{s}}_{E,M}\right),$$

Flavor decomposition of the vector form factos:

$$\boxed{G^p_{E,M}} = \frac{2}{3}G^{\mathbf{u}}_{E,M} - \frac{1}{3}\left(G^{\mathbf{d}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) , \quad \boxed{G^p_{E,M}} \text{well known}$$

$$\boxed{G^n_{E,M}} = \frac{2}{3}G^{\mathbf{d}}_{E,M} - \frac{1}{3}\left(G^{\mathbf{u}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) , \quad \boxed{G^n_{E,M}} \text{relatively well known}$$

$$\widetilde{G}^p_{E,M} = (1 - \frac{8}{3}\sin^2\theta_W)G^{\mathbf{u}}_{E,M} - (1 - \frac{4}{3}\sin^2\theta_W)\left(G^{\mathbf{d}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) ,$$

$$\widetilde{G}^n_{E,M} = (1 - \frac{8}{3}\sin^2\theta_W)G^{\mathbf{d}}_{E,M} - (1 - \frac{4}{3}\sin^2\theta_W)\left(G^{\mathbf{u}}_{E,M} + G^{\mathbf{s}}_{E,M}\right) ,$$

We have 5 unknowns: $\widetilde{G}^p_{E,M}$, $\widetilde{G}^p_{E,M}$, $G^u_{E,M}$, $G^d_{E,M}$, $G^s_{E,M}$; and 4 equations. Thus, if, experimentaly, one measures, for instance, $G^s_{E,M}$ the equations can be trivially solved.

Flavor decomposition of the axial-vector form factos:

$$
\begin{aligned}
G_A^p &= -G_A^{\mathbf{u}} + G_A^{\mathbf{d}} + G_A^{\mathbf{s}}\,, \\
G_A^n &= G_A^{\mathbf{u}} - G_A^{\mathbf{d}} + G_A^{\mathbf{s}}\,.
\end{aligned}
$$

Flavor decomposition of the axial-vector form factos:

$$
\begin{aligned}
G_A^p &= \boxed{-G_A^{\mathbf{u}} + G_A^{\mathbf{d}}} + G_A^{\mathbf{s}}\,, \\
G_A^n &= \boxed{G_A^{\mathbf{u}} - G_A^{\mathbf{d}}} + G_A^{\mathbf{s}}\,. \\
\boxed{2G_A^{(3)}} &= G_A^{\mathbf{u}} - G_A^{\mathbf{d}}\,, \text{ determined by } \beta\text{-decay measures}
\end{aligned}
$$

Flavor decomposition of the axial-vector form factos:

$$\begin{aligned} G_A^p &= \boxed{-G_A^{\mathbf{u}} + G_A^{\mathbf{d}}} + G_A^{\mathbf{s}}\,, \\ G_A^n &= \boxed{G_A^{\mathbf{u}} - G_A^{\mathbf{d}}} + G_A^{\mathbf{s}}\,. \\ \boxed{2G_A^{(3)}} &= G_A^{\mathbf{u}} - G_A^{\mathbf{d}}\,, \text{ determined by } \beta\text{-decay measures} \end{aligned}$$

We have 2 equations and 3 unknows. If, experimentally, one measures, for instance, $G_A^{(s)}$ the equations can be trivially solved.

The observable PV asymmetry is defined as

$$\mathcal{A}^{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$\mathcal{A}^{PV} = \frac{\mathcal{A}_0}{G}\Big[-(1-4\sin^2\theta_W) + \varepsilon G_E^p(G_E^n + \boxed{G_E^{(s)}}) + \tau G_M^p(G_M^n + \boxed{G_M^{(s)}}) + \delta'(1-4\sin^2\theta_W)G_M^p G_A^p\Big]$$

The study of PV Asymmetry allow us to explore the Electric and Magnetic Strangeness of the Nucleon: $\boxed{G_E^{(s)}}$ and $\boxed{G_M^{(s)}}$.

The observable Ratio is defined as

$$\mathrm{R} = \frac{\sigma_{p,^{12}C} + \sigma_{H_2}}{\sigma_{n,^{12}C} + \sigma_{p,^{12}C} + \sigma_{H_2}}$$

The study of the Ratio allow us to explore the Axial Strangeness of the Nucleon: $G_A^{(s)}$.

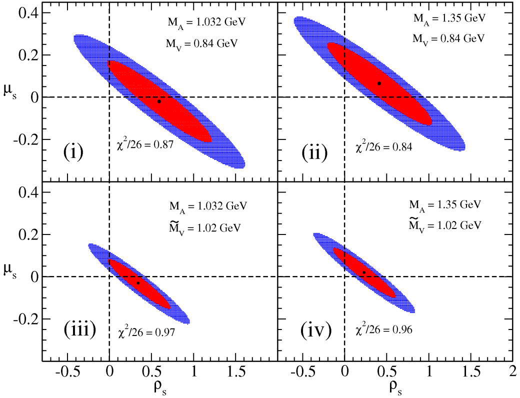

Figure: World data constraint in the $\mu_s - \rho_s$ plane. The red (dark) and blue ellipses represent 68.27% ($1\sigma \Rightarrow \Delta\chi^2 = 2.30$) and 95.45% ($2\sigma \Rightarrow \Delta\chi^2 = 6.18$) confidence contours around the point of maximum likelihood (black). Each panel corresponds to different values of the dipole axial mass, M_A, and dipole (monopole) vector strange mass, M_V